

# Constraints on millicharged particles by neutron stars

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We have constrained the charge-mass ( $\varepsilon - m$ ) phase space of millicharged particles through the simulation of the rotational evolution of neutron stars, where an extra slow-down effect due to the accretions of millicharged dark matter particles is considered. For a canonical neutron star of  $M = 1.4 M_\odot$  and  $R = 10$  km with typical magnetic field strength  $B_0 = 10^{12}$  G, we have shown an upper limit of millicharged particles, which is compatible with recently experimental and observational bounds. Meanwhile, we have also explored the influences on the  $\varepsilon - m$  phase space of millicharged particles for different magnetic fields  $B_0$  and dark matter density  $\rho_{\text{DM}}$  in the vicinity of the neutron star.

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## I. INTRODUCTION

Since Zwicky (1933) proposed the problem of the “missing mass”, the theoretical and experimental studies on dark matter (DM) have attracted more and more attention. It is well-known that the total energy of the Universe contains about 27% DM and about 5% baryon matter as well as about 68% dark energy according to the most recent cosmological results based on Planck measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra [1]. In recent years, experimental physicists have concentrated their attention on the direct and indirect detections of DM particles. Direct search experiments aim to detect individual interactions, i.e., DM particles scatter off target nuclei of detectors, such as DAMA [2], CDMS II [3], CoGeNT [4], CRESST-II [5], XENON100 [6], LUX [7], PandaX [8] and so on. Indirect detection experiments mainly probe annihilation or decay products (gamma-rays, neutrinos and charged cosmic rays) of DM, such as AMS-02, PAMELA, Fermi-LAT, IACTs, IceCube, ANTARES, Super-K [9, 10]. From a theoretical point of view, several candidates of DM particles are supposed, for example, neutralinos [11, 12], Majorana neutrinos and technibaryons [13, 14]. In this paper, we are interested in another candidate of DM in the form of millicharged (MC) particles [15–17].

The electric charge of all the particles in the Standard Model appears to be an integer multiple of  $e/3$ , where  $e$  is the charge of the electron. However, MC particles have electric charge  $e' = \varepsilon e$ , where  $\varepsilon$  is any real number and  $\varepsilon < 1$ . They can be either bosons or fermions. MC particles were first proposed in order to solve the DM puzzle a long time ago [15, 18, 19]. Hereafter millicharged dark matter particles (MCDM) have been studied extensively (see Ref. [16] and

references therein). It is worth noticing that Huh *et al.* [20] presented a possible explanation of the 511 KeV galactic  $\gamma$ -ray due to positron productions from MCDM. MC particles have an obvious impact on the standard picture of the Universe in many ways. Firstly MC particles can significantly influence the expansion rate of the Universe and the baryon-to-photon ratio during the epoch of big bang nucleosynthesis (BBN) in the early Universe [21–23]. Secondly, MC particles also may explain the creation of galactic magnetic fields at the cosmological epoch of the galaxy formation [24]. Thirdly, the anisotropy power spectrum of the CMB is affected by MC particles in several respects [25, 26].

At present MC particles are already constrained by experimental and observational data [21, 23, 27–29], including the  $\varepsilon - m$  ( $m$  is the mass of MC particle) phase space and the fraction of MC particles. These existing constraints on MC particles mainly contain laboratory bounds (including the limits from experiments searching for MC particles [27, 30]), cosmological bounds (BBN, CMB anisotropy) and constraints from stellar evolution (globular clusters, white dwarfs, red giants, and supernova 1987A). For very light MC particles,  $m < 1$  keV, the reactor experiments show a strict limit  $\varepsilon < 10^{-5}$  [31]. For MC particles that are lighter than electrons,  $m < m_e$ , the best particle physics bound  $\varepsilon < 3.4 \times 10^{-5}$  is given from the data that ortho-positronium decay to dark matter pairs [32]. For heavier MC particles,  $m > m_e$ , the bounds become weaker [27]. For  $m = 1$  MeV, the bound is  $\varepsilon < 4.1 \times 10^{-5}$ , and for  $m = 100$  MeV, the bound is up to  $\varepsilon < 5.8 \times 10^{-4}$ . If the MC particles become heavier than 100 MeV, the bound  $\varepsilon \sim 10^{-2}$  is allowed, while for  $m > 1$  GeV it can be as large as  $\varepsilon = 0.1$ .

With the discovery of neutron star (NS) by Bell and Hewish [33], the properties of NS have been studied by many theoretical and experimental physicists [34–37]. NS is a compact star, which is characterized by strong gravitational field, electromagnetic field, extreme strong and weak interaction. Thus it is usually regarded as a “natural laboratory” with extreme physical condition. At present it seems that all currently observed pulsar periods mainly lie between milliseconds and a

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few seconds. As it can be seen from the  $P - \dot{P}$  ( $P$  and  $\dot{P}$  are the spin period and its time derivative, respectively) diagram (see Fig. 1), most radio pulsars have a period of around one second and the period derivatives in the range of  $10^{-16}$  to  $10^{-14}$  s  $s^{-1}$ . However, one group of sources having higher magnetic field ( $10^{13-15}$  G), relatively long periods ( $>1$  s), and high period derivatives ( $10^{-13} - 10^{-9}$  s  $s^{-1}$ ) are magnetars. The other group of sources are millisecond pulsars with old age ( $\sim 10^9$  yr) and lower magnetic field ( $10^{8-9}$  G). In the ATNF pulsar catalogue [38], the longest spin period for normal radio pulsars to date is  $\sim 8.51$  s of PSR J2144-3933 whose characteristic age is  $2.72 \times 10^8$  yr and surface magnetic field is  $2.08 \times 10^{12}$  G [39]. Except for short-lived glitches [40], the rate of rotation of a NS drops steadily as a function of time, especially for millisecond pulsars which have very low values of  $\dot{P}$  and very low timing noise. It is generally believed that the spin-down of the NS is due to magnetic dipole radiation (MDR) and electromagnetic torques in the magnetosphere [41].

Limits on DM from neutron stars have been deeply investigated in a large amount of literatures so far [42–50]. Recently, Kouvaris and Perez-Garcia [17] have discovered that the electric charges could be expelled from the star as MCDM are accreted onto the NS. The escaping charged particles will provide an extra current, thus the torque is produced. They find that this mechanism yields an extra spin-down of neutron stars and the braking indices can be substantially smaller than 3 predicted by the MDR model.

We follow the philosophy of Kouvaris and Perez-Garcia [17], but explore how to constrain the  $\varepsilon - m$  of MC particles via the currently observed pulsar periods. We consider the effect of the additional torque by the extra currents due to the accretions of MCDM onto the NS on the period of pulsars. We also impose a limit of pulsar's period in the  $P - \dot{P}$  diagram on the period's evolution equation as a cut-off. By doing so, the  $\varepsilon - m$  of MC particles will be constrained under the given DM density.

This paper is organized as follows. Firstly, we revisit the mechanism of the accretions of MCDM onto the NS (electromagnetic accretion), then the rotational evolution equations of a NS considered the MDR and the torques, which are produced by the Goldreich and Julian (GJ) current [51]  $I_{GJ}$  and the extra current  $I_{DM}$ , are shown in Section 2. Secondly, we numerically show the bounds of the  $\varepsilon - m$  of MC particles in Section 3. Finally, we present the conclusions in Section 4.

## II. THE MODELS

First we show how the accretions of MCDM onto the NS can lead to an excess of currents [17]. If the Larmor radius  $r_L = \frac{mv_\perp}{eB}$  of MCDM is much smaller than the curvature radius  $R_{\text{curv}} = |\frac{1}{B} \frac{dB}{dr}|^{-1}$ , it may follow the magnetic field lines in the magnetosphere within the light cylinder of the NS and cross the surface of the star.  $v_\perp$  is the particle's velocity perpendicular to the magnetic field  $B$ . As the accumulations of MCDM trapped in the NS, once the Coulomb repulsive force becomes larger than the gravitational force, the electric charges will be expelled from the star. The expelled charges are in the form

of either electrons or protons, which depend on the charge of the accreted MCDM. Once the equilibrium between the accretions of MCDM and the expulsions of electric charges has been established, stable extra currents will be formed.

As stated previously, the slow-down of the rotation powered pulsars is due to the MDR and the braking torques provided by the outflowing plasmas [52]. The rotational kinetic energy loss rate of the NS is  $\dot{E} = I\Omega\dot{\Omega} = -L$ , where  $I$  and  $\Omega$  are the moment of inertia and the angular velocity of the star, respectively, and  $L$  can be expressed as two components [53]

$$L = L_{\text{orth}} \sin^2 \theta + L_{\text{align}} \cos^2 \theta. \quad (1)$$

In the above equation,  $L_{\text{orth}}$  represents the “orthogonal” case that the angular momentum of the star is decreased by the MDR,  $L_{\text{align}}$  represents the “aligned” case that the torque is produced by the electric current from escaping charged particles that follow the open magnetic-field lines in the magnetosphere of the NS, and  $\theta$  is the angle between the rotational and the magnetic axes (magnetic inclination angle). The two components can be written as

$$L_{\text{orth}} = \frac{B_0^2 \Omega^4 R^6}{4c^3}, \quad L_{\text{align}} = \frac{B_0 \Omega (\Omega - \Omega_{\text{death}}) R^3 I}{2c^2}, \quad (2)$$

where  $B_0$  and  $R$  are the magnetic field strength on the polar cap (the open magnetic-field lines in the light cylinder connect to the surface of the star) and radius of the star, respectively,  $c$  is the light speed, and  $\Omega_{\text{death}}$  is the angular velocity below which the pulsar emission dies. The total current  $I$  can be written as the sum of  $I_{GJ}$  and  $I_{DM}$ ,  $I = I_{GJ} + I_{DM}$ , where  $I_{GJ}$  represents the emission of relativistic charged particles from the surface cap regions ( $\sim \pi R_C^2$ ,  $R_C$  is the polar cap radius) of the NS, due to a particle acceleration gap potential  $V_{\text{gap}}$  of the order of  $10^{12}$  V [54] that develops along open magnetic field lines in the vicinity of the polar cap, and  $I_{DM}$  represents the extra current from the expelled electric charges (electrons or protons) due to the accretions of MCDM onto the NS.

According to the pioneering work of Goldreich and Julian [51], the GJ current is  $I_{GJ} = \pi R_C^2 \rho_{GJ} c$ , where  $\rho_{GJ}$  is the GJ charge density. The polar cap radius can be expressed as  $R_C = R \sin \theta_p = R(R/R_L)^{1/2}$ , where  $\theta_p$  is the angle of the polar cap to the center of the star and  $R_L = cP/2\pi$  is the light cylinder radius [55]. In the polar cap region, the GJ charge density is given by [51]

$$\rho_{GJ} = 7 \times 10^{10} e \left( \frac{B_0}{10^{12} \text{ G}} \right) \left( \frac{s}{P} \right) \text{ cm}^{-3}, \quad (3)$$

thus, we can easily deduce

$$I_{GJ} \simeq 1.4 \times 10^{30} e \left( \frac{B_0}{10^{12} \text{ G}} \right) \left( \frac{s}{P} \right)^2 \text{ s}^{-1}. \quad (4)$$

For the extra current  $I_{DM}$  due to the accretions of MCDM onto the NS, we directly adopt the results in Ref. [17],

$$I_{DM} \simeq 1.0 \times 10^{29} e e \left( \frac{\rho_{DM}}{0.3 \text{ GeV cm}^{-3}} \right) \left( \frac{1 \text{ GeV}}{m} \right) \left( \frac{P}{s} \right) \text{ s}^{-1}. \quad (5)$$

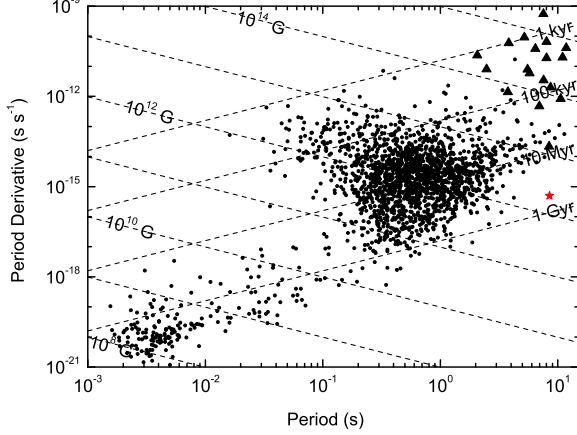


FIG. 1: Distribution of all known pulsars on the  $P - \dot{P}$  diagram. Dots are rotation powered pulsars (including normal pulsars and millisecond pulsars, which dominate the pulsar population) (from ATNF: <http://www.atnf.csiro.au/research/pulsar/psrcat/>). Triangles are magnetars (from McGill magnetar catalog: <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>). The red star denotes the famous PSR J2144-3933, which has the longest spin period for normal radio pulsars. The dash lines of pulsar characteristic age are defined by  $P/(2\dot{P})$  and another dash lines of surface dipole magnetic field are conventionally defined as  $3.2 \times 10^{19}(P\dot{P})^{1/2}$ , which are based on the MDR.

Finally, using the Eqs. (1) and (2), we can get the rotational evolution equation of the NS

$$\frac{d\Omega}{dt} = -\frac{B_0^2 \Omega^3 R^6}{4I c^3} \left[ \sin^2 \theta + \left( 1 - \frac{\Omega_{\text{death}}}{\Omega} \right) \left( 1 + \frac{I_{\text{DM}}}{I_{\text{GJ}}} \right) \cos^2 \theta \right]. \quad (6)$$

We define  $\lambda = \frac{I_{\text{DM}}}{I_{\text{GJ}}}$  for convenience. As we can see from Eq. (6), it easily recovers the scene of the MDR for  $\lambda = 0$  (no extra current). It is worth noticing that we can take  $\frac{\Omega_{\text{death}}}{\Omega} \ll 1$  safely, since normal pulsars couldn't be older than  $10^7$  to  $10^8$  years. We compare the evolution curve of period from Eq. (6) with that from the scene of pure MDR. Fig. 2 shows the differences between them. It is obvious from Fig. 2 that the differences become larger gradually as the increases of age. We use the 8.51 s period at  $2.72 \times 10^8$  yr (which are the observational data of PSR J2144-3933) as the cut-off of neutron stars, because it is the longest observed period of normal pulsars and possible longer period should fall below the so-called "death line" on the  $P - \dot{P}$  diagram, where pulse emission can't be observed. As shown in Fig. 1, the location of PSR J2144-3933 on the  $P - \dot{P}$  diagram indicates that the star could be a good candidate as the cut-off for the period evolution and the characteristic age of normal radio pulsars. However, both the millisecond pulsars and magnetars are unsuitable to constrain the  $\varepsilon - m$  of MC particles. It is generally believed that the millisecond pulsars have a complicated and turned evolution. Recycling neutron stars to millisecond periods may be a key process. Additionally, the extra current  $I_{\text{DM}}$  is much smaller than the corresponding GJ current  $I_{\text{GJ}}$  according to Eq. (4) for

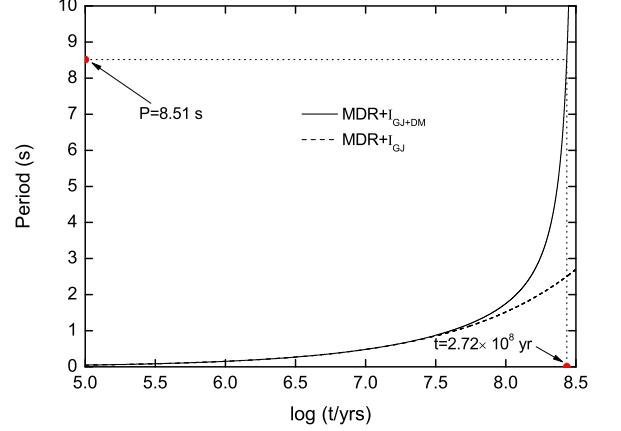


FIG. 2: The period evolution of a canonical NS with  $M = 1.4 M_\odot$  and  $R = 10$  km for  $B_0 = 10^{12}$  G. The dash curve represents the spin-down induced by pure MDR ( $\lambda = 0$  in Eq. (6)). The solid curve shows an extra slow-down of the NS with magnetic inclination angle  $\theta = 45^\circ$  by the additional torque due to the accretions of MCDM with  $m = 1$  GeV and  $\varepsilon = 5.04 \times 10^{-2}$ . The labels for the red dots represent the 8.51 s period at  $2.72 \times 10^8$  yr.

millisecond pulsars. The tiny differences have no imprint in Fig. 2 even if we overlook the recycled processes. For higher magnetic fields, there are only 28 currently known magnetars and magnetar candidates [56]. The physics of magnetars is unclear so far. Their emission is probably powered by the non-rotational kinetic energy or by their decay of super-strong magnetic field [57, 58]. The pure MDR model may not be a good description for magnetars. Therefore, we think that it is seriously inaccurate and unreliable to constrain the parameters of MC particles by magnetars.

### III. NUMERICAL RESULTS AND DISCUSSIONS

For convenience, we assume that the star consists of non-superfluid neutrons, protons and electrons, and suppose that the density of the star is uniform. In our calculations, we consider a canonical NS of  $M = 1.4 M_\odot$  and  $R = 10$  km, and take the initial period  $P_0 = 1$  ms, the moment of inertia of the star  $I = \frac{2}{5}MR^2 \approx 10^{45}$  g cm<sup>2</sup>, and the local DM density in the vicinity of the NS  $\rho_{\text{DM}} = 100 \times 0.3$  GeV/cm<sup>3</sup> (0.3 GeV/cm<sup>3</sup> represents the standard DM density around the Earth).

The  $\varepsilon - m$  phase space of MC particles could be constrained using the following strategy. First, we plug a great number of groups of  $(\varepsilon, m)$  into Eqs. (4), (5) and (6) for various magnetic field strength and different magnetic inclination angles under the given DM density in the vicinity of the NS. Then, we simulate Eq. (6) up to  $2.72 \times 10^8$  yr as the cut-off for the age of the NS. If the evolution of the rotational period of the star exceeds the longest observed period of normal radio pulsars to date ( $\sim 8.51$  s), we consider this group of  $(\varepsilon, m)$  invalid.

The  $\varepsilon - m$  phase space of MC particles constrained by a

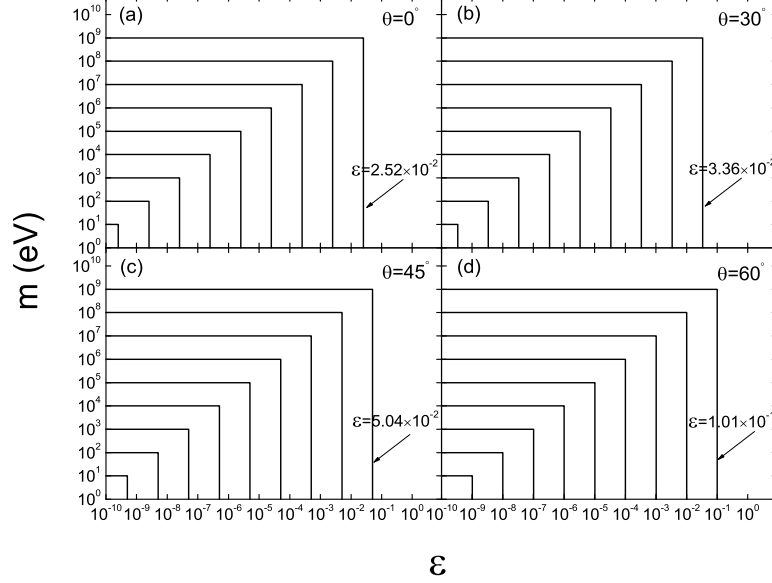


FIG. 3: The  $\varepsilon - m$  phase space of MC particles constrained by a canonical NS of  $M = 1.4 M_{\odot}$  and  $R = 10$  km with  $B_0 = 10^{12}$  G for different magnetic inclination angles.

canonical NS of  $M = 1.4 M_{\odot}$  and  $R = 10$  km with typical  $B_0 = 10^{12}$  G for different magnetic inclination angles is shown in Fig. 3. It can be seen from Fig. 3(a) that the charge of MC particles can reach up to  $\varepsilon = 2.52 \times 10^{-2}$  for heavier particles with  $m = 1$  GeV, the bound  $\varepsilon > 2.52 \times 10^{-5}$  is ruled out apparently for MC particles with  $m = 1$  MeV, and the limit  $\varepsilon \leq 2.52 \times 10^{-8}$  is allowed for lighter particles with  $m = 1$  KeV. Furthermore, if the mass  $m$  decreases by one order of magnitude, the charge  $\varepsilon$  would reduce by the same one order of magnitude. As shown above, the lighter the mass, the smaller the charge. It is obvious from Eq. (6) that the rotational angular velocity of the star could decrease rapidly as  $\lambda$  increases for the same magnetic field strength  $B_0$ , which result in the rise of the spin period even to the unreasonable value. Fig. 3(b), (c) and (d) show that the upper limit of  $\varepsilon$  is inversely proportional to  $\cos^2 \theta$  for the same mass  $m$  of MC particles (see Eq. (6)). To summarize, we would present an upper limit of MC particles,  $(\frac{1 \text{ GeV}}{m}) \times \varepsilon \leq 2.52 \times 10^{-2} / \cos^2 \theta$ , which is consistent with experimental and observational bounds [27, 31, 32].

It is worth stressing that, as shown in Eq. (6), the rate of deceleration of the rotation  $\dot{\Omega}$  also depends on the magnetic field strength  $B_0$ . For  $B_0 = 10^{11}$  G, the bounds become weaker, the charge  $\varepsilon$  of MC particles can't be constrained for heavier particles with  $m = 1$  GeV, however up to  $\varepsilon \leq 3.26 \times 10^{-3} / \cos^2 \theta$  for  $m = 1$  MeV and  $\varepsilon \leq 3.26 \times 10^{-6} / \cos^2 \theta$  for lighter particles with  $m = 1$  KeV. On the other hand, it can be seen from Eq. (5) that, the extra current  $I_{\text{DM}}$  relies on the DM density  $\rho_{\text{DM}}$  in the vicinity of the NS. Although  $\rho_{\text{DM}}$  around the NS is uncertain to date, we could draw a conclusion that, the larger the DM density, the smaller the charge for the MC particles with the same mass, e.g., if the DM density  $\rho_{\text{DM}}$  increases by

one order of magnitude, the charge  $\varepsilon$  would decrease by one order of magnitude correspondingly for the same mass  $m$  of MC particles.

#### IV. CONCLUSIONS

We have constructed the constraints of the  $\varepsilon - m$  of MC particles by neutron stars based on an enhanced slow-down of neutron stars due to an extra current yield by the accretions of MCDM. For a canonical NS of  $M = 1.4 M_{\odot}$  and  $R = 10$  km with typical magnetic field strength  $B_0 = 10^{12}$  G, we have shown an upper limit of MC particles,  $(\frac{1 \text{ GeV}}{m}) \times \varepsilon \leq 2.52 \times 10^{-2} / \cos^2 \theta$ , which indicates the charge would be smaller as the mass of MC particles becomes lighter and is compatible with experimental and observational bounds. The specific limits are as follows, the charge of MC particles could rise to  $\varepsilon = 2.52 \times 10^{-2} / \cos^2 \theta$  for heavier particles with  $m = 1$  GeV, the bounds  $\varepsilon \leq 2.52 \times 10^{-5} / \cos^2 \theta$  and  $\varepsilon \leq 2.52 \times 10^{-8} / \cos^2 \theta$  are allowed for the MC particles with  $m = 1$  MeV and  $m = 1$  KeV, respectively, i.e., if the mass  $m$  decreases by one order of magnitude, the charge  $\varepsilon$  would reduce by the same one order of magnitude. However, for the NS with lower magnetic fields ( $10^{10-11}$  G), the bounds become weaker. In particular, for millisecond pulsars ( $10^{8-9}$  G) and magnetars ( $10^{13-15}$  G), it is not appropriate to bound the  $\varepsilon - m$  of MC particles. In addition, we have also investigated the influence on the  $\varepsilon - m$  of MC particles for the different DM density  $\rho_{\text{DM}}$  in the vicinity of the NS. It is obvious that, the larger the DM density, the smaller the charge for the MC particles with the same mass.

The model we adopted is uniform stellar configuration.

However, it is well-known that the neutron stars constructed by the realistic equations of states can be approximated as the uniform case. Our work have shown an upper limit of the  $\varepsilon$ - $m$  of MC particles based on the new mechanism, and the results will be unchanged in the order of magnitude when considering the realistic equations of states.

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